U.S. DEPARTMENT OF ENERGY | OFFICE OF Cybersecurity, Energy Security, and Emergency Response

Time-Sensitive QKD
GE Research

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Cybersecurity for Energy Delivery Systems (CEDS) Peer Review

October 6-7, 2020

Project Overview

Objective

- Provide industrial & utility networks with fast, deterministic, simple, and secure communication.
- Leverage synergy between time-sensitive networking (TSN) and quantum key distribution (QKD) -> time-sensitive quantum key distribution (TSQKD)

Schedule: Oct 1, 2018 – Sep 31, 2021

Report on target demonstration scenario	3/31/2019
Report on design alternatives for integration of QKD with TSN	9/30/2019
Report on commercialization plan	9/30/2019
Standards-based YANG network management model	9/30/2019
Report on optical chip integration requirements and benefits	12/31/2019
Report on Time-Sensitive QKD-integrated architecture and technology gaps	9/30/2019
Time-Sensitive QKD scheduling software report	9/30/2020
Report on technologies for implementing integrated QKD chip architectures and filling identified gaps	3/31/2020
Report on Time-Sensitive QKD test suite	9/30/2020

Total Value of Award: $3,932,157

Funds Expended to Date: 74.44%

Performer: GE Research

Partners: Qubitekk, MITRE, EPB

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Advancing the State of the Art (SOA) I

- *Describe current "state of the art"*
  - Classical RSA cryptography (RSA), Diffie-Hellmann (DH), Public Key Infrastructure (PKI), Post-Quantum Cryptography (PQC).
  - Alice & Bob Quantum Key Distribution (QKD) equipment: $10K+ each, box-sized, requires utilities (power, cooling water) and routine maintenance.
  - Quality-of-Service (QoS) and traffic isolation achieved through virtual Local-Area Networks (LAN) and basic prioritization.
- *Describe the feasibility of your approach*
  - Fiber connections used to implement QKD.
  - Time-Sensitive Network (TSN) provides deterministic communication with per stream QoS and flow control (Ethernet).
- *Describe how your approach is better than the SOA*
  - Simpler and more difficult to compromise; eavesdropper detected.
  - New Photonic Integrated Chip (PIC) design enables low-cost, low-form factor QKD for all edge devices on power grid.

Advancing the State of the Art (SOA) II

- *Describe how the end user of your approach will benefit*
  - Simpler, lower-cost, more secure.
  - Enables a converged, fully-characterized network.
- *Describe how your approach will advance the cybersecurity of energy delivery systems*
  - TSN enforces flow patterns at nanosecond resolution that resist cybersecurity attacks by restricting traffic injection.
  - QKD physical layer key generation and distribution improvement over classical cybersecurity and TSN enables low-cost control of Measurement-Device-Independent (MDI) QKD.
    - Eavesdropper (Eve) detection, high key entropy, simpler.
- *Describe the potential for sector adoption*
  - QKD standardization
    - Institute of Electrical and Electronics Engineers (IEEE) P1913 Software-Define Quantum Communication.
    - European Telecommunications Standards Institute (ETSI).
    - International Telecommunication Union (ITU).

Progress to Date

Major Accomplishments

- Patents (~8 filed):
  - Combining measurement device independent-quantum key distribution (MDI-QKD) and time-sensitive networks (TSN).
  - Time-sensitive network (TSN) scheduling with QKD.
  - QKD protection of TSN flows.
  - QKD-protected TSN time synchronization.
- Pathways for Sector Adoption:
  - IEEE P1913 – Software-Define Quantum Communication (YANG model).
  - Good communication/collaboration with GE businesses who supply utilities with communication and control equipment.
- Key Discoveries:
  - **Photonic integrated circuit (PIC) chip design for edge devices & TSN compatible mode of operation analyzed.**

Progress to Date

Milestones

- Designed grid solution with QKD-protected TSN
  - Including QKD authentication and encryption of TSN configuration.
- Developed qkd-linuxptp to integrate QKD-enabled Linux generalized Precision Time Protocol (gPTP) with the qkd-distributor.
- Eavesdropper designed and remote programming operation partially implemented.
- Designed simplified key mapping that assigns the keys based on actual data flows.
- Designed Time-Sensitive QKD (TSQKD) technology using grid standards and integrated into legacy equipment:
  - Distributed Network Protocol (DNP3) integrated with Secure SCADA Protocol for the 21st century (SSP21) over TSN.
  - Quantum symmetric keys used with IEC 61850 Routable-Generic Object-Oriented Substation Event (R-GOOSE) authenticity and encryption.

Challenges to Success

Challenge 1: Competition from PQC (post quantum cryptography), which tries to overcome quantum computing with increased complexity

- Steps taken to overcome challenge: keep informed of PQC progress, mostly funded by NIST, and discuss classical methods with GE experts.

Challenge 2: First attempt to secure time synchronization (gPTP) for TSN

- Designed and implemented QKD authentication for all time synchronization messages.

Challenge 3: Reducing operational complexity

- Leveraged TSN constructs for protected data streams and centralized network configuration to distribute keys.

Challenge 4: Expensive, large, high-maintenance equipment required for QKD implementation

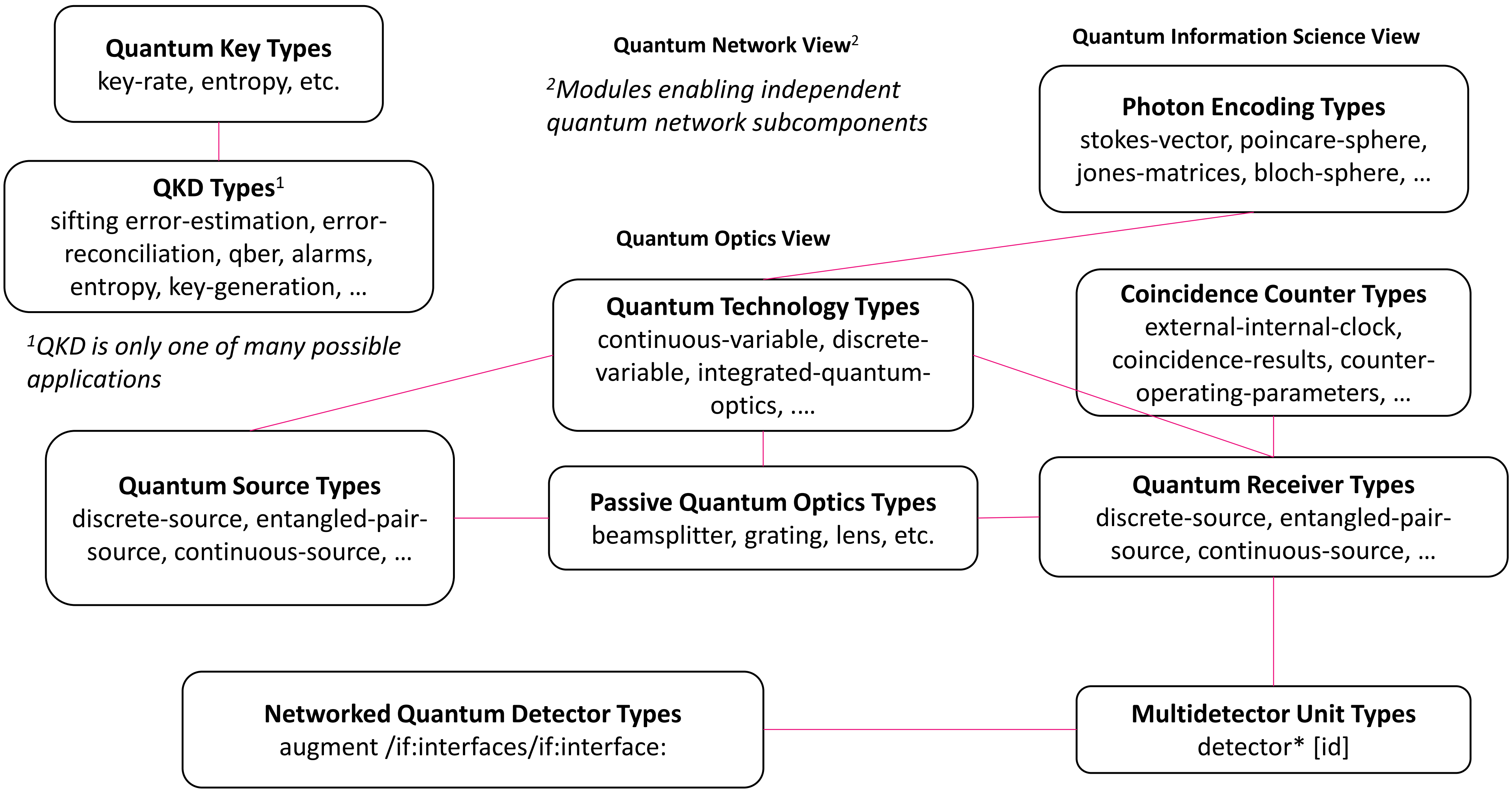
- QKD approach that can be implemented entirely within PIC chips at edge devices without expensive equipment.
- Amortize QKD technologies across Intelligent Electronic Devices (IED) in a substation (@ 20 IEDs/substation, a $50k QKD device = Δ$2.5k/IED…closer to manageable).

Collaboration/Sector Adoption

- **Plans to transfer technology/knowledge to end user**
  - What category is the targeted end user for the technology or knowledge? (e.g., Asset Owner, Vendor, OEM)
    - QKD for utility asset protection could be used both by a utility (asset owner) and their OEMs, such as GE's Grid Automation business.
  - What are your plans to gain industry acceptance?
    - Wavelength division multiplex all classical traffic (QKD and duplex data) to eliminate the need for additional fiber when introducing QKD to a link.
    - Insert into GE Grid Automation's Mutli-Generational Product Plan (MGPP) and look for (1) customer funded pilot installations that will (2) lead to outward year insertion.
    - Zero extra configuration by OT staff will be key to lowest total installed cost.
    - **Funding for a follow-on project will be required to reduce MDI-QKD PIC to practice**
  - Describe testing and demonstrations planned:
    - Demonstration of R-GOOSE quantum encrypted communications on commercial product, GE Grid Solutions Universal Relay (to be setup with GE Grid Solutions).
  - What is the timeline for demonstration and sector adoption?
    - Demonstration at EPB is in 2021. Sector adoption depends on further developments, costs, and competition (e.g., PQC).

Collaboration/Sector Adoption

IEEE P1913 Quantum Communication NETCONF/YANG Standard



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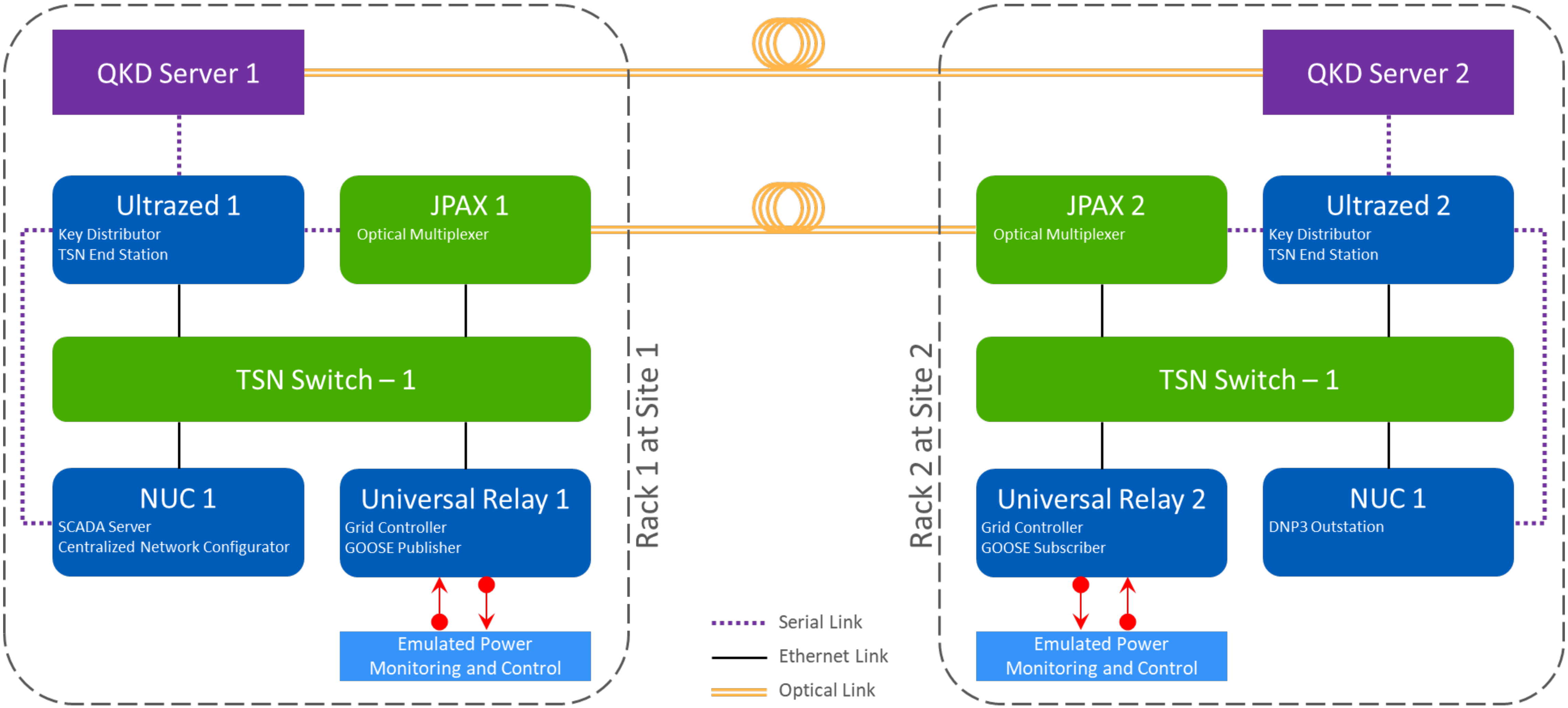
Next Steps for this Project

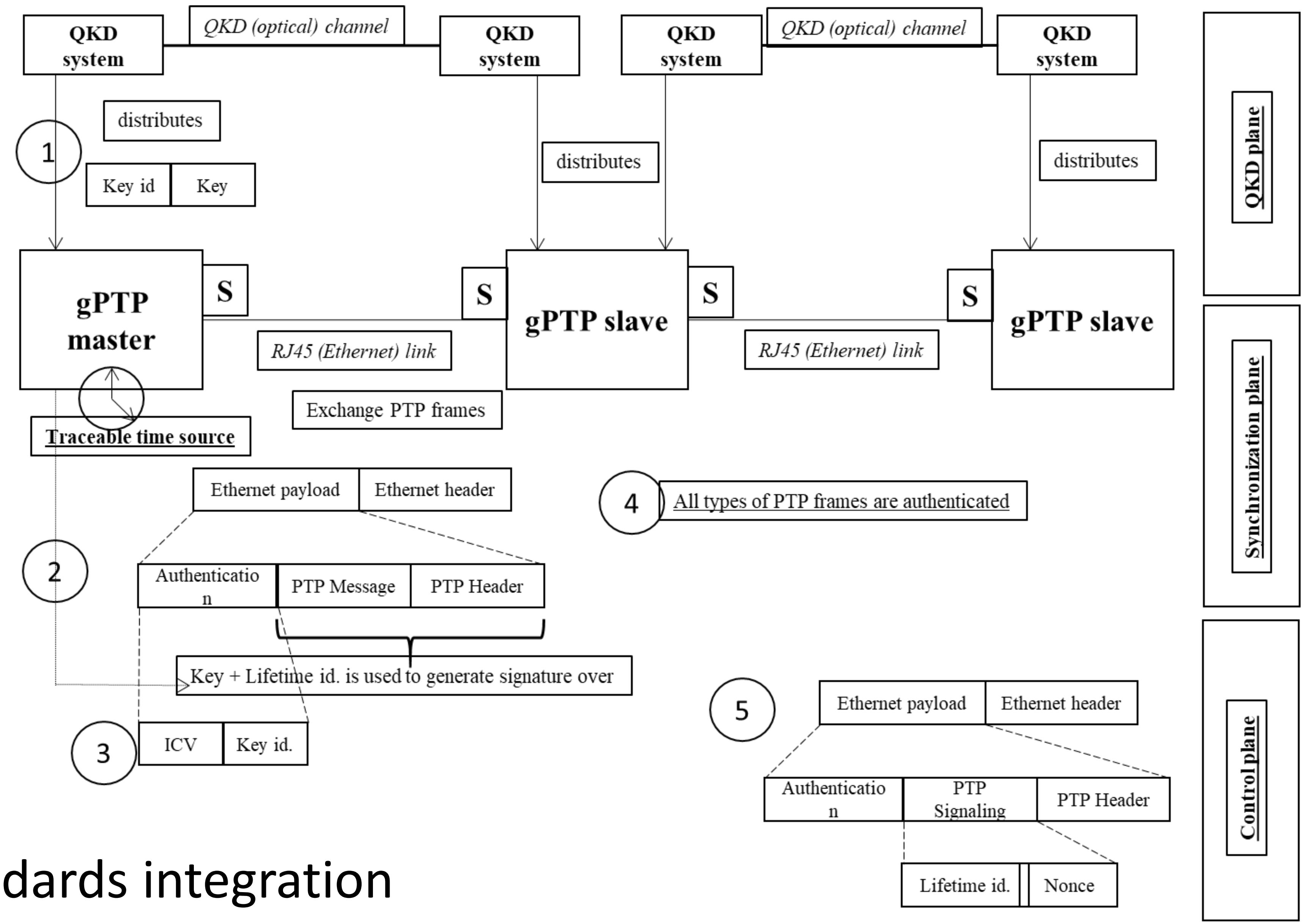
Approach for the next year or to the end of project

- Key Milestones to accomplish
  - Integration of all the networking and QKD components for Phase II
  - Field Test Automation
  - During demo of project, test ability of equipment to detect eavesdropper using variable fiber optic splitter (remotely operated)
- Upcoming significant events
  - Successful demonstration of our TSQKD equipment and approach at EPB utility in Chattanooga with Qubitekk

Planned TSQKD Substation Racks

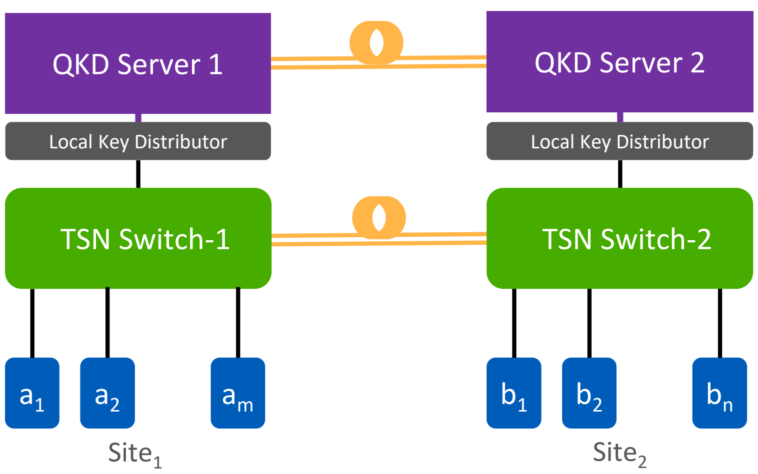


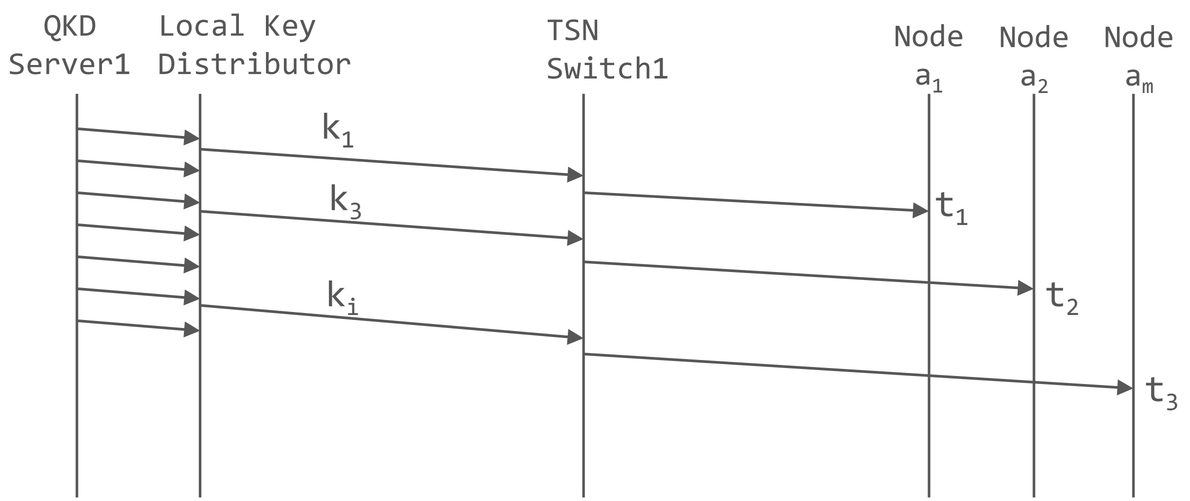
QKD-Protected Time Synchronization for TSN



Standards integration

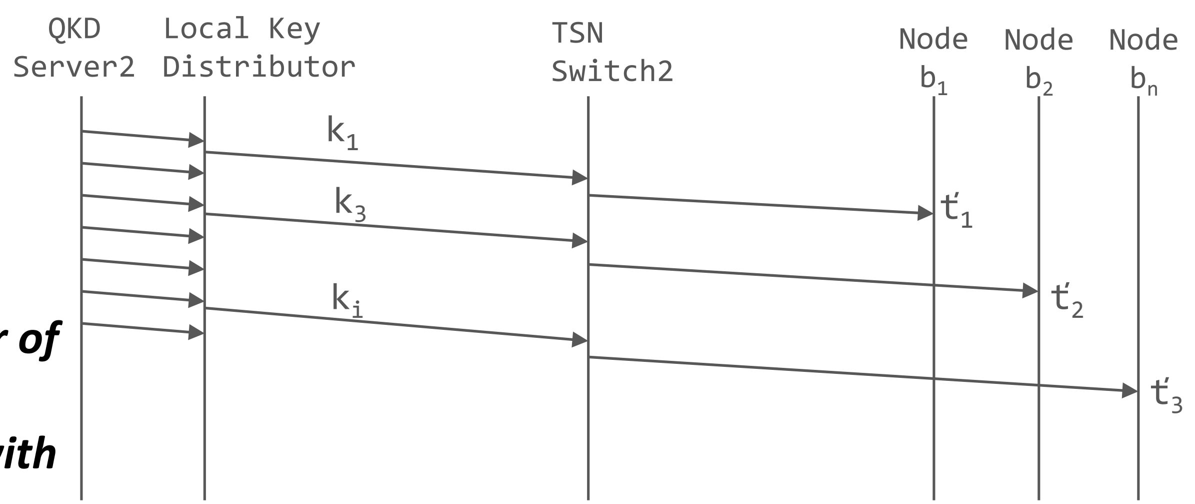
TSQKD Deterministic Key Delivery





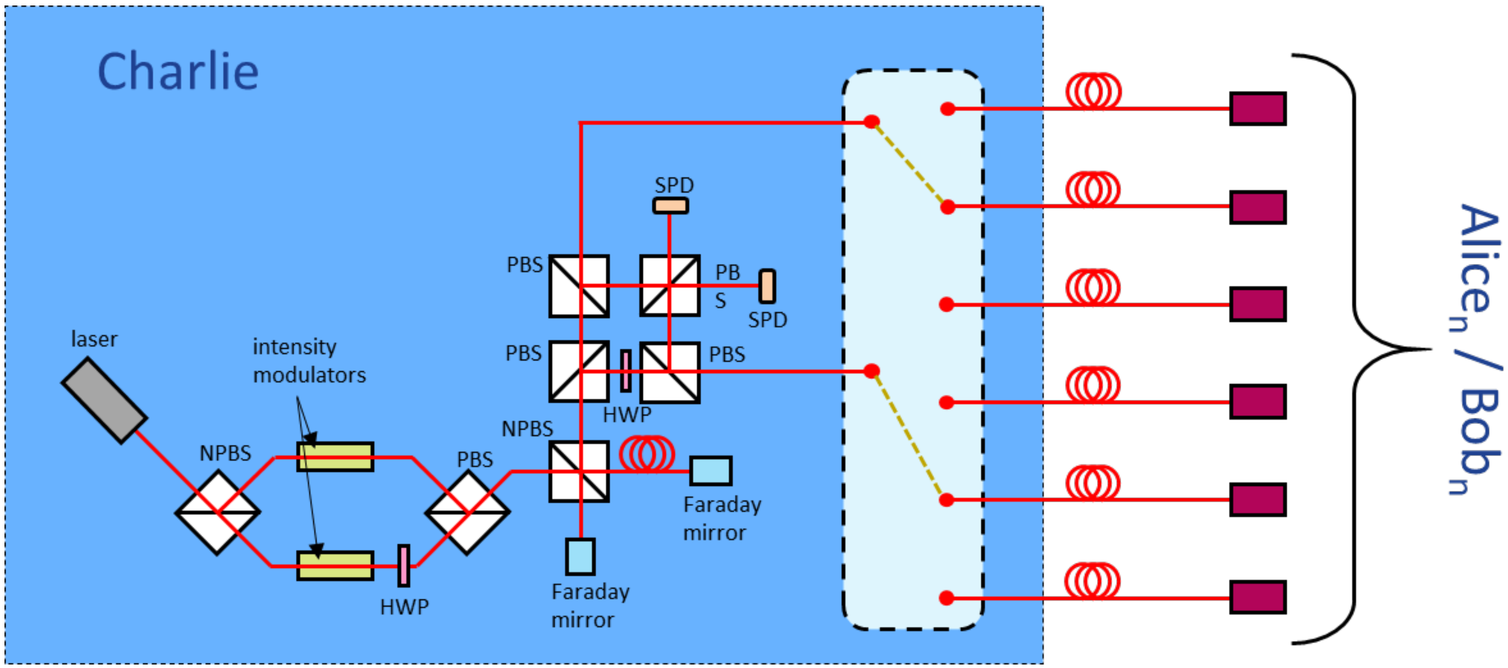
$|t_1 - t'_1|$ =peak-to-peak PDV error of TSN network under the presence of uncontrolled traffic.

In a typical TSN network:
$|t_1 - t'_1| < 100$ ns



TSN delivers keys on isolated ethernet links to a pair of communicating nodes (Alice and Bob) at the exact same time. Basically synchronous delivery of keys with an error < 100 nsec

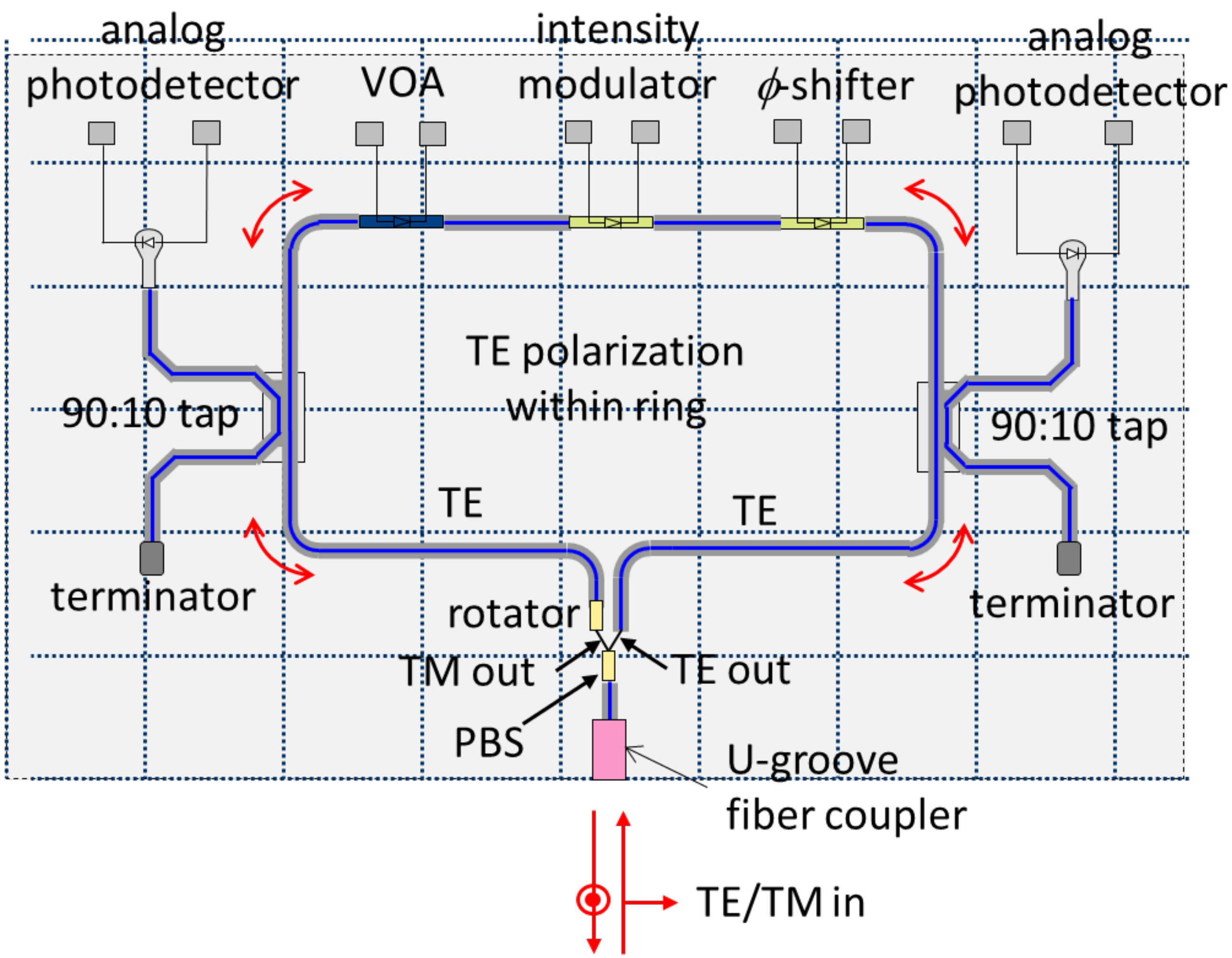
QKD network with PIC chips for MDI-QKD



TSN-controlled

PIC chip design for Alice / Bob

Small, low-cost, ubiquitous QKD on a chip



Funding for a follow-on project will be required to reduce MDI-QKD PIC to practice

TSN-Synchronized Quantum Internet LAN

Coincidence control example…